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Annual Performance Report for

Development of a Long Wavelength Optical Receiver for Phased Array Antenna Systems NCC3-252

K. P. Roenker, S. M. Frimel and M. J. Soucek
Department of Electrical and Computer Engineering
University of Cincinnati
Cincinnati, Ohio 45221-0039

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This report summarizes our progress in the last year in the design and development of optical receivers for phased array antenna systems. The report consists of summaries of work in three main areas: metal-semiconductor-metal (MSM) photodetectors, heterojunction bipolar transistors (HBTs) and optical receivers. In each case design, fabrication and characterization results are summarized.

Metal-Semiconductor-Metal (MSM) photodetectors

During the last year considerable progress has been made in designing, fabricating and characterizing these MSM photodetectors. A simple two-mask set was designed based on a two interpenetrating comb pattern for the MSM configuration and various finger widths and spacings as well as various detector areas. The mask layout was accomplished using the HP Microwave Design System (MDS) software and the masks fabricated in the mask shop in the department. To aid in the MSM design, computer simulations using MATHMATICA were performed to assess the effects of device parameter choices (finger width and spacing, etc.) on the expected high frequency performance of the device. MSMs with a one micron finger width and one, two and three micron finger spacing and 100 micron square detectors were designed to meet the 13 GHz frequency bandwidth requirement of the receiver. Using the above described photodetector mask set, MSM's were fabricated using GaAs substrates and aluminum metal to form short wavelength (850 nm) detectors initially. Dark current measurement on these MSM detectors show very small (hundreds of pA's) leakage currents, which are comparable or better than those reported in the literature. Capacitance versus bias measurements were also made on these MSM photodetectors to verify the very small (pF) capacitances that make these devices attractive. Next, photoresponse measurements were made to determine the optical performance of these devices. The photocurrent versus bias was measured using illumination with a 850 nm laser. The optical power was measured using a HP power meter to be $10.7\mu W$ at the end of the optical pigtail fiber which was positioned over the photodetector using an xyz micromanipulator. The low photocurrent observed here (of the order of 100 nA) corresponds to a photoresponse of only about 0.01 A/W which is relatively low compared to published reports of 0.1 to 0.5 A/W. This can be due to a number of factors including issues associated with the measurement of the optical power delivered to the device, alignment of the fiber to the MSM, reflection losses and excessive recombination of carriers at the surface which can be reduced by using a surface passivation layer such as silicon nitride which can also serve as an antireflection coating.

Long wavelength MSM photodetectors are under development based on InGaAs as the absorbing medium. Using our inhouse epitaxial growth facilities epitaxial substrates have been prepared using InGaAs lattice matched growth on InP substrates. However, due to the very low Schottky barrier heights known to exist for metals on InGaAs, an intervening layer of a wider bandgap material is necessary. Our initial attempt employed a thin InAlAs layer (50 nm) over a 2 μ InGaAs absorbing layer and MSM photodetectors were fabricated using the mask set described above. Leakage currents were measured and found to be much larger (μA's) than seen for the GaAs MSMs (pA's). This is attributed to the poor quality of the InAlAs layer, which was later verified by photoluminescence and x-ray diffraction measurements, which arises from a high defect density. Subsequent growths of higher quality InAlAs by other investigators here at the university have demonstrated higher quality film growth at higher growth temperatures near 700 ^{o}C versus the 640 ^{o}C employed here. Future plans call for use of a thin, wide gap InP layer in place of the InAlAs layer to enhance the Schottky barrier height since it can be grown at the lower temperature and has been reported in the literature as being successfully used for this purpose in MSM photodetectors. Also measured was the photocurrent generated in the presence of light which showed approximately a 3 μA increment over the dark current corresponding to a responsivity of 0.177 A/W. Taking into account reflection and shadowing losses we expect a responsivity of 0.23 A/W. Hence, the optical performance of this device is reasonably good, with the exception of the very poor leakage current. The better optical response seen here for the InGaAs MSM is probably attributable to the much lower surface recombination velocity of this material as compared with GaAs so that many more carriers survive (are not lost to surface recombination) to be collected. As in the GaAs case, a silicon nitride or possibly a polyimide anti-relection layer will also be added to further improve performance. Finally, for both GaAs and InGaAs MSMs, Ti/Pt/Au metallization will be investigated for integration of the MSM fabrication process with that of the HBTs in the final receiver fabrication process.

Heterojunction Bipolar Transistors (HBTs)

The approach to receiver development taken in this work has been based on employing the heterojunction bipolar transistor (HBT) as the active device for use in the preamplifier. This selection was based on the high gain and superior high frequency performance of the device without the need for submicron lithography. During the last year our efforts with regards to HBTs have been concentrated on the fabrication of AlGaAs/GaAs and InP/InGaAs devices with the former for use in the short wavelength (850 nm) receiver while the InP-based HBT for use in the long wavelength (1350 nm) version. To minimize the number of masks to be fabricated, the same self-aligned fabrication process was chosen for both with changes in the fabrication processes, e.g. different metals and etching solutions, as needed. Included in the composite mask design for the HBT test chip are discrete transistors, microwave padded transistors for on chip s-parameter measurements and specialized test structures for device and fabrication process characterization. Since these devices and this self-aligned process have not been previously fabricated on campus for either of these material systems, the initial portion of this work has entailed the development of the various processes such as selective etching solutions and techniques, isolation techniques, metallization systems and a self aligned fabrication process to build these HBTs.

For the AlGaAs/GaAs HBTs epitaxial substrates with the desired layers were purchased from Kopin Corporation and employed in the fabrication process. Because the device layers are extremely thin, particularly the base region which is only 100 nm thick, and because there must be uniformity across the wafer during etching to simultaneously fabricate a multitude of devices, the fabrication process requires precise control. To aid in achieving etching uniformity across the wafer, the use of selective etching solutions that preferentially etch either the AlGaAs or GaAs were investigated and developed. Based on the periodical literature, for the

AlGaAs hydrofluoric acid was chosen as the etchant since it is known not to attack GaAs. For the GaAs etch, citric acid was selected since it gives a high selectivity to AlGaAs. Experiments were undertaken to determine the optimum concentrations, temperature and other etch parameters for the desired selectivity and reasonable etch rates. Using the above described process an initial fabrication process was performed. While problems were encountered as described below, processing was continued to complete the fabrication process. While fully functional HBTs were not obtained during this initial run, and they usually are not for the first fabrication attempt for almost any device, there were a number of successes that could be identified. First, the metal depositions and electrical contacts formed were successful. Ohmic contacts were formed with each of the three device regions (emitter, base and collector) and the total series resistance for each was measured using a test structure. In general, the contact resistances were low with the emitter showing the highest result which may be due to the fact that the metal contact layers were not optimized and may have been excessively thermally annealed which would degrade their characteristics. This is not considered to be a serious problem as this contact metallurgy has been used here before with good success. A second major success of this initial fabrication run is the fact that the self-aligned process was successfully demonstrated. As proof, the emitter and base contacts were not found to be shorted together, which is what is anticipated when the self-aligned base etch does not produce the desired undercut and the metallization is not correct. The emitter-base characteristic shows the conventional diode shape with minimal reverse leakage current and a sharply increasing current in forward bias above a cutin voltage of about 1.6 V. For the base-collector current-voltage characteristic, again a diode-like characteristic is seen as expected indicating that the junction has not been shorted by, for example, an overetching of the base region causing the base metal to penetrate thru to the underlying collector and short. A second fabrication run was aborted when a silicon nitride capping layer failed due to pinholes and the device layers were inadvertently etched away. A third fabrication process run has just been successfully completed and device characterization is beginning. The results of measurements on these devices will be used in the finalization of the receiver's design.

For the long wavelength receiver, InP/InGaAs HBTs have been under development using inhouse epitaxial growth facilities to fabricate the initial multilayer substrates. For these InP-based materials the composition must be precisely controlled to ensure lattice matched, device quality materials. A series of calibration growths has been performed to determine appropriate growth parameter settings for composition and doping. Based on these results, several wafers were grown with an npn InP/InGaAs structure were the appropriate layer structure was determined by device simulations. These substrates were used to begin developing the fabrication process for npn InP/InGAaAs HBTs utilizing the above described mask set, but with different metallization (Ti/Pt/Au) and etching processes. To develop a selective etching process, an H_3PO_4:H_2O_2:HCl mixture was investigated based on reports in the literature. In the absence of the hydrogen chloride, the solution will etch InGaAs but not InP; in the absence of the hydrogen peroxide, the solution will etch InP but not InGaAs. The appropriate mixtures giving good selectivity and desirable etch rates were experimentally determined and an initial attempt at fabricating InP-based HBTs was performed. Partial success was achieved in that wafer were carried through the fabrication to completion, but working transistors were not obtained. Several successes can be identified from the results. First, ohmic contacts were demonstrated for each of the device layers with contact resistances of 100 to 200 ohms which include bulk series resistances. Second, base-emitter and base-collector junction characteristics were measured and diode-like characteristics observed. While junction leakage currents were excessive, the results again demonstrated that the self-aligned fabrication process was operation. Third, the etching solutions and process worked reasonably well in that the device structure was formed and contact made to the desired layers. Future work will examine refinements in the epitaxial growth process to improve the quality of the epitaxial layers and so device junction quality. In addition, because of difficulties in the fabrication process associated with the use of silicon nitride and ion implantation isolation, several changes were made in the mask set design and the use of polyimide as a final passivation layer has been investigated and developed. This revised process and mask set has been used in the latest AlGaAs/GaAs HBT fabrication run and will be used in future InP/InGaAs HBT fabrications.

Optical Receiver Design

Work has also been in progress on the design of the HBT-based amplifier for use in the receiver. A number of circuit configurations have been simulated using the HP Microwave Design System software to investigate their microwave performance as compared with the system requirements. For these simulations, theoretical estimates of HBT device parameters have been used based on an inhouse program for device modelling based on the device's structure and its epitaxial layers. Finalization of the receiver's design, or designs if space allows in the mask layout, is awaiting experimental measurements of actual device performance. In these simulation studies tradeoffs in the receiver's design have been investigated, particularly bandwidth versus gain. The unusually large bandwidth (6-13 GHz) dictated by the need for the receiver to carry both the data channel at 6-8 GHz and the reference signal at 12.5 GHz places added difficulties in the design. As an alternative, the design of a dual, narrow channel receiver where the signal is split after detection into data and reference signals and separately amplified is also being investigated. There is also a tradeoff involved here in that more complex designs require more transistors which makes the likely fabrication yield lower. Finally, the receiver's fabrication process is being examined and developed. It must integrate the MSM and HBT's fabrication, but also incorporate additional features such as interconnects, capacitors, resistors and other components for circuit integration. Along this line, metal-insulator (silicon nitride)-metal capacitors and titanium thin film resistors have been under development with good preliminary results.